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Plastic ablator ignition capsule design for the National Ignition Facility

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Abstract. This paper describes current efforts to develop a plastic ablator capsule design for the first ignition attempt on the National Ignition Facility. The trade-offs in capsule scale and laser energy that must be made to achieve ignition probabilities comparable to those with other candidate ablators, beryllium and high-density carbon, are emphasized. Large numbers of 1-D simulations, meant to assess the statistical behavior of the target design, as well as 2-D simulations to assess the target's susceptibility to Rayleigh-Taylor growth are discussed.

1. Introduction

Three types of ablator material are currently under study for the for the National Ignition Facility (NIF) ignition capsule [1]: beryllium doped with copper, plastic (CH) doped with germanium, and nano-crystalline synthetic diamond doped with tantalum. Each of these materials shows various strengths and weaknesses that recommend it as the first choice ablator. Equally, each of these capsule ablator materials has been intensively investigated both theoretically and experimental. This paper summarizes the current state of the CH capsule design, as represented by a large data base of simulations run with the radiation hydrodynamics code LASNEX [2]. As these designs constantly evolve in response to improved physics modeling and experimental input, it should be recognized that this paper is necessarily a snapshot of a work in progress.

2. 1-D design considerations

The current CH ablator capsule design is shown in Fig. 1. A layer of cryogenic DT ice lines the inside of a spherical ablator shell. The inner region of the ablator is doped with high- Z germanium to adjust the x-ray opacity, while the outer region, which makes up the majority of the material ablated, is left undoped. The modification of the opacity introduced by the doping is designed to minimize the unstable Atwood number that develops at the fuel-ablator interface at peak velocity. The presence of the high- Z dopant strongly absorbs the incident x-ray flux leaving the undoped layer of the ablator closest to the fuel colder and hence denser than the rest of the ablator. The precise concentration of dopant and width of the doped layer are carefully adjusted taking into account the anticipated hard x-ray flux.

In addition to the capsule dimensions and compositions, the 1-D design is characterized by a tuned radiation pulse shape giving good entropy and implosion velocity. Fig. 2 shows the radiation temperature pulse shape used to drive the capsule. The radiation temperature is extracted from an integrated hohlraum simulation including laser beam propagation and

absorption and accounting for expected losses due to laser-plasma interactions. The total laser power used in the integrated hohlraum simulation is also shown. When properly tuned, the four shocks launched by this pulse shape implode the capsule with the low fuel averaged entropy of 0.447 kJ/mg/eV and high implosion velocity of 0.384 mm/ns.

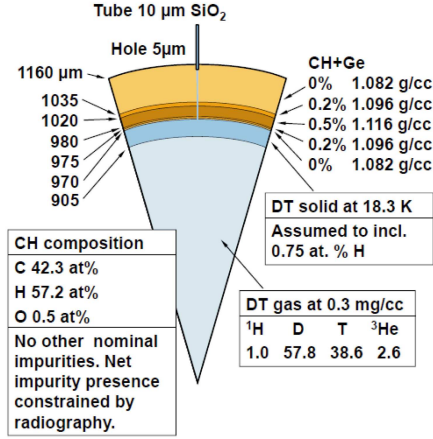


Figure 1. “Pie diagram” for the current CH capsule design.

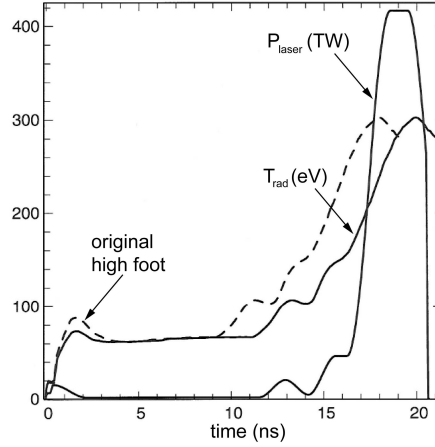


Figure 2. Four-step pulse shape used to drive the CH capsule.

3. Low- and intermediate-mode stability

Once the 1-D considerations of implosion velocity and entropy have been adequately tuned, the 2-D and 3-D considerations of hydrodynamic stability can be addressed. These considerations broadly break down into low mode perturbations which dominate the perturbations around the igniting hot spot and intermediate and high mode perturbations which threaten the shell integrity near peak velocity. Low-mode perturbations are assessed using simulations that include the complete 180° angular extent of the capsule and typically resolve modes up to Legendre mode number $\ell = 30$ with roughness applied to all of the interfaces of the capsule: the inner ice surface, fuel-ablator interface, the internal dopant layers, and the outside of the ablator. Fig. 3 shows the results of such simulations plotted as yield versus multiplier applied to the nominal ice surface roughness. The low-mode yield curve for CH is compared to the analogous yield curve for a beryllium ablator capsule design, showing that the CH design achieves comparable to or slightly higher low-mode robustness.

The effects of intermediate modes are assessed by performing single-mode Lagrangian simulations with infinitesimal perturbations applied to the ablator outer surface and extracting linear growth factors at peak velocity at the ablation front. Fig. 4 shows these ablation front growth factors for modes $\ell = 10 - 160$. The nominal capsule design uses the latest tabular equation of state (EOS) for CH, LEOS 5310, which is more compressible than the earlier table LEOS 5105. The significant increase in peak growth factor with the latest and most accurate EOS compared to the earlier table is apparent.

Also shown in the figure are the growth factors resulting from an earlier version of the design using the latest EOS but a pulse shape with a higher picket on the foot of the pulse (also shown in Fig. 2 as the dashed curve). The stronger first shock with the higher foot reverses the phase of the growth factors in the mode range $\ell = 100 - 150$ relative to the low foot. Since fabricated CH shells show features (surface bumps) in this mode range, the enhanced growth factors for $\ell = 100 - 150$ lead to unacceptable perturbations to the shell and necessitated shifting to the lower foot pulse shape.

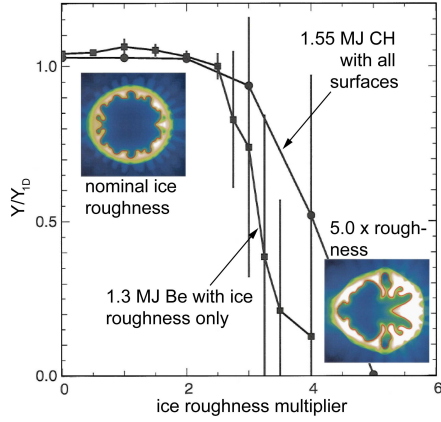


Figure 3. Capsule yield normalized to 1-D versus initial ice roughness for a beryllium ablator design (■) and the CH design (●). Each data point represents an average of seven simulations with different realizations of the random surface roughnesses. The error bars give the variance of the yields. Example hot spots are shown as insets.

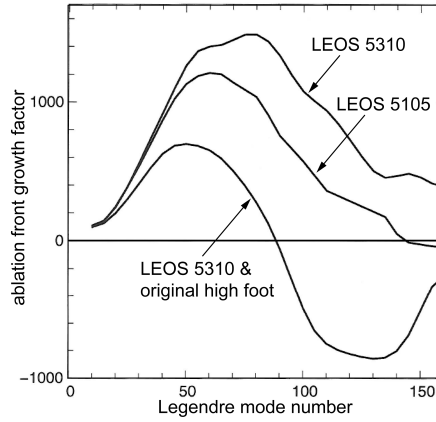


Figure 4. Growth factors for ablator surface perturbations at peak velocity for Legendre mode numbers $\ell = 10 - 160$. Curves for the nominal CH EOS, LEOS 5310, and an earlier, less compressible EOS, LEOS 5105, are shown. Also shown are the negative growth factors that result from using an earlier high-foot pulse shape.

The instability effects that occur at very high modes, notably at the classically unstable fuel-ablator interface and generated by the presence of the glass fill tube, are also critical to the design and are described elsewhere [3].

4. Statistical assessments of robustness

In addition to optimizing the capsule design in 1-D and ensuring its stability in 2-D, it is important to recognize that a variety of random defects can occur in any given capsule or in the laser performance from shot to shot. Assessing the effects of these random defects requires a statistical approach. The approach followed here was pioneered and extensively developed by Salmonson for the beryllium ablator design [4]. It consists of tabulating all possible random sources of error to be expected under actual experimental conditions, bracketing those sources of error within specified bounds and with specified statistical distributions, and then generating a data set of random instantiations of the given capsule design with all sources of error. Once the full data set has been run, the simulations may be post-processed to extract, for example, the distribution of expected yields given the assumed uncertainty.

Fig. 5 summarizes the results of such a study on the current CH capsule in the space of capsule yield versus ignition threshold factor (ITF), a measure of capsule performance relative to the threshold of ignition and previously referred to as capsule margin. It can be represented as a product of capsule scale, implosion velocity, fuel averaged entropy, and hot spot perturbation fraction and has been shown to be a reliable predictor of capsule performance [5]. Three data sets are shown in the figure: each of the red dots represents an instantiation of the 1-D capsule design including all 1-D errors with all deviations drawn from nominal distributions, *i.e.*, as expected under experimental conditions. There are 10,000 total instantiations sampled. Each of the blue dots represents a similar 1-D instantiation but with deviations drawn from distributions with twice the width of the nominal distributions. Finally, the green triangles show the results

of sub-sampling the 1-D nominal deviations into 2-D by including nominal roughnesses on all interfaces. The total 2-D data set consists of seventy simulations.

What is immediately evident from Fig. 5 is that the CH capsule design is highly robust in 1-D as well as 2-D. With nominal deviations, none of the capsules sampled in 1-D or 2-D failed in the sense of yielding less than 1.0 MJ. Even with the deviations doubled in 1-D, only one instantiation gave a yield less than 1.0 MJ. The utility of the data set with double nominal deviations becomes apparent here since the ITF is normalized by the location of the yield cliff, by definition $ITF = 1.0$. The location of this cliff is ambiguous with the data set of nominal deviations and only becomes apparent with the double nominal distributions. With this normalization, the nominal 1-D design, without any deviations, is located at $ITF = 5.5$. With the addition of 1-D nominal deviations, the ITF is degraded to between 2.0 and the original 5.5. With the addition of 1-D double nominal deviations, the distribution of ITF increases further to the edge of the yield cliff. Finally, the cloud of green triangles indicate that with nominal deviations in 2-D an average ITF of approximately 3.0 can be expected.

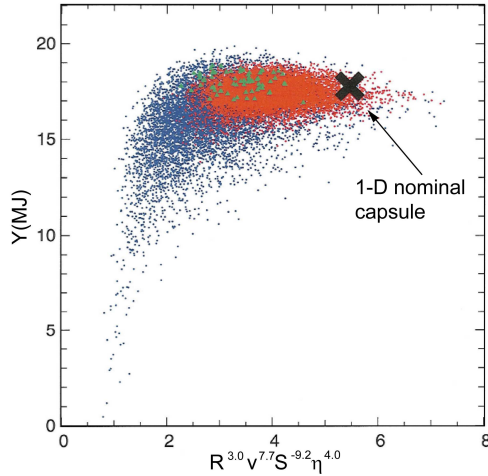


Figure 5. Results of statistical scans over all expected capsule defects summarized as a scatter plot of yield versus ITF. The red ensemble is the result of 10,000 1-D samples with nominal deviations, the blue ensemble is the result of 10,000 1-D samples with double nominal deviations, and the green ensemble results from sub-sampling the 1-D nominal ensemble into 2-D including random roughnesses on all interfaces.

5. Conclusions

This paper summarizes the current state of the plastic ablator ignition capsule design for NIF. Broadly, a balance has been sought between the many competing considerations of 1-D performance optimization, 2-D stability requirements, and 1-D and 2-D statistical reliability in an effort to reach a design most likely to achieve ignition. Further revisions of the design will necessarily continue as physics understanding improves and new experimental data become available.

Acknowledgments

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